EVIDENCE CONCERNING THE EOLIAN ORIGIN OF THE CANYONS SURROUNDING THE NORTHERN MARTIAN POLAR CAP

Presented in partial fulfillment of
the requirements for the degree
Bachelor of Science in the Department
of Geology and Mineralogy of
The Ohio State University

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1978

Fall Quarter

Approved by G. Faure
Advisor

ACKNOWLEDGEMENTS

I wish to thank Dr. John Raymer, Dr. Lonnie Thompson, and Ellen Thompson, all from the Ohio State University, for their help regarding this thesis. I especially want to thank Dr. Gunter Faure for his advice and constructive criticism of this thesis, which have improved its quality greatly. Finally, I wish to acknowledge the National Space Science Data Center for supplying the images that helped make this thesis possible.

ABSTRACT

A hypothetical southeasterly wind may be responsible for the eolian carving of the canyons in the southern-most sector (N78° to N83° by 330° to 360°) of the North Polar Cap of Mars. The wind belongs to the annual Martian dust storm and has an average temperature of 240°K with a speed of 300 meters per second. The wind should strike the ice cap from the southeast or east-southeast, sublimating and transporting volatiles and dust toward the North Pole. The material should be deposited just north of the canyon heads on the slope of Dzurisin's and Blasius's (1975) possible four-kilometer-high ridge. This ridge may explain the relatively short lengths of these particular canyons by the rapid cooling of the heated air as it is forced to rise to higher elevations. The wind will precipitate its volatiles, producing possible dune fields near the canyon heads. Evidence for the southeasterly wind is lacking in itself, but the canyons have eolian features that parallel a northwest-southeast axis for such a wind direction.

INTRODUCTION

The purpose of this paper is to test the hypothesis of the eolian origin of the peripheral canyons on the southern-most sector of the northern Martian ice cap through the use of the geological and meteorological information available for the area. The sector being studied is within the latitudes of N78° to N83° by 330° to 360° west longitude. The geological and meteorological information will give some insight to the origin of these canyons by the interaction of the atmosphere with the topographic features in the region.

This area was first observed by Mariner 9's wide-angle camera. These images revealed short canyons which vary in width from 8 to 15 kilometers and have lengths of less than 200 kilometers. The canyons have the configuration of a counterclockwise spiral, eminating from the north-northwest with the heads located at about the N81.5° latitude. (See Plates 1 and 2.)

On September 30, 1976; Viking 2 executed an orbital maneuver that allowed the high-resolution camera to take highly magnified images of the region. This manruver modified Viking 2's orbit from a 52° inclination to a new orbit with a 75° inclination. The spacecraft then passed approximately 2350 kilometers at a slant range from the designated peripheral canyons taking high-resolution images. The author has obtained high-resolution images for scattered areas within the previously defined sector plus an additional image of several canyons outside this sector. Unfortunately, much of this sector had not been photographed by the high-resolution camera, and only three of the images overlap.

The designated peripheral canyon area has a variety of topographic features which cover about 100,000 square kilometers.

(See Figure 1.) All of the large canyons are oriented on a NW - SE axis, and terraces are common at the mouths of these larger canyons. The most prominent features within the larger canyons are broad terraces found in Plates 3, 4, and 5. (Coincidently, all three of the previously mentioned plates overlap, covering a central portion of the canyon area in the designated sector.) Another important set of topographic features found in the above three plates and Plate 6 are the steep canyon and terrace walls. These walls expose a stratigraphy of laminated dust and snow layers that appear equally thick and have lateral continuity extending for hundreds of kilometers (Cutts, 1973a). Finally, there appears to be a series of wind-carved hills with smooth slopes on the terraces and canyon floors that the author yardangs. These yardangs strongly suggest eolian erosion with the long axis of these laminated hills paralleling the canyon walls. Elsewhere, smaller canyons present at the edge of the ice cap seem to have features similar to those of the larger canyons but are oriented on a NE - SW axis. Below these canyons are low-lying plains with massive dune fields girdling the peripheral edge. Another observation that must be noted is that very few meteorite craters are seen in the designated area. Many of the previously mentioned features and images will be referred to again in this analysis.

The designated canyonland is relatively young because its lack of cratering. All the scientists who have examined the returned imagery agreed that very few craters can be found on or around the ice cap. This statement on the relative age is based on the assumptions as stated by Nash (1974,p389): (1)"that the influx of meteorites has been of relatively uniform intensity and distribution; (2) that the geomorphic processes that are degrading the craters have also been of uniform intensity and distribution; and (3) that all areas are equally craterable." The geomorphic processes involved are wind blown sand and/or dust surrounding the ice cap and the deposition of dust and either snow or frost over the ice cap. Either process will obliterate or bury impact craters and both are still active at the present time.

The origin of these peripheral canyons has been studied by geologists. Their~~s~~ hypotheses apply to all the swirling canyons in both the northern and southern polar regions. Murray and Malin (1973,p997) proposed the idea of polar wandering. They hypothesized that "... the former position of Mars' spin axis may be recorded by the centers of curvature of the displaced circular topographic features of the laminated terrain." Presumably, each terrace and canyon wall marked a former equatorward limit of the deposition of volatiles and dust or where erosion has removed enough volatiles and dust until erosion no longer acts on that particular plate. Later, a new plate of more volatiles and dust would be deposited over the peripheral of the first plate and thus the sequence continues. As one can ess, they do not elaborate on the erosional process(es) that formed the peripheral canyons nor are the plates circularly symmetrical over the others. This hypothesis will not be considered in view of these and other shortcomings.

Clark and Mullin(1976) presented the glaciation hypothesis. They proposed that the laminated deposits are predominantely dry ice. As a flowing glacier, the depositional layers were sheared to reveal the stratification. This hypothesis is highly improbable, because carbon dioxide is an unlikely major constituent for either pole due to the summer temperature readings of 205°K versus the 148°K temperature needed for dry ice. Furthermore, water ice will not easily deform or fracture under the existing polar temperatures and stresses. (Kieffer et al., 1976; Sharp, 1974)

Cutts (1973b) suggests that the canyons and terraces were eroded by prevailing winds blowing off the pole, as applied to the South Pole. However, he admits that the spiraling canyons may have been formed by more complex circulation patterns over the polar regions. The author agrees with the observation of the prevailing northeasterly winds over the northern polar cap. The observed winds generally flow from the NE, carrying snow and dust off the ice cap onto the surrounding plain. Though this wind carries some debris, it is not responsible for the cutting of the large canyons that are situated on a NW - SE axis. The canyon size suggests the need for a very strong wind with great cutting power acting along this NW - SE axis. Two interrelated assumptions will have to be made for the coming hypothesis. First, the peripheral canyons have an eolian origin. Second, that no northwesterly wind flows off the ice cap that would be unusually stronger than the present northeasterly winds. The author will propose a warm and very strong southeasterly or east-southeasterly wind as associated with the annual Martian dust storm. This wind will ? both the cutting power in heat and particulate matter plus the velocity in very high speeds and proper direction. The author will pursue this hypothesis in attempting to demonstrate its credibility.

DATA AND ANALYSIS

The first topic of major importance to this region is the present chemical composition of the Martian atmosphere. Its composition by mass is: 96 percent carbon dioxide, 2.5 percent nitrogen, 1.5 percent argon, 0.1 percent oxygen, and traces of krypton and xenon (Leovy, 1976). Water vapor over the Martian ice cap is 0.1 percent by mass of the atmosphere. In terms of relative humidity, this is the saturation point for this atmosphere to support water vapor.(Metz,1976). The important gases that influence climate and surface conditions are water and carbon dioxide. Both gases are volatiles that precipitate or sublimate with the seasonal changes at the polar caps.

The physical parameters of this atmosphere also vary~~s~~ with the seasons. The atmospheric pressure at the surface averages 6.5 millibars as indicated by the Viking landers. The landers have made continual measurements from the surface that have shown some variation in pressure with the high pressure of 9 millibars and the low of 6 millibars. This change is attributed to water vapor and carbon dioxide being precipitated or sublimated at the poles as the planet undergoes seasonal changes (Masursky, 1977, private communication). These pressures are very low when compared with the earth's average surface pressure of 1,013 millibars. Likewise, the atmospheric density varys from 0.01549 kilograms per cubic meter at a summer temperature high of $205^{\circ}K$ ($-68^{\circ}C$) on the ice to 0.02145 kilograms per cubic meter at $148^{\circ}K$ ($-125^{\circ}C$), the condensation point for carbon dioxide. These atmospheric density figures have been calculated with a constant surface pressure of 6.5 millibars and an atmosphere composed entirely of carbon dioxide. One factor that was not compensated for in the atmospheric densities, was the significant wind speeds.

The wind speeds on the surface of Mars have been measured from a few meters per second to 135 meters per second (or 300 miles per hour).(Weaver, 1973) This wind speed of 135 meters per second was recorded in the 1971 dust storm by Mariner 9. The wind speeds associated with these dust storms are believed to be important in the origin of the peripheral canyons. This topic will be discussed later in this paper.

The second major topic will be the types of transport of loose particles and their ability to erode a surface. Sagan and Pollack (1969) gave general descriptions of the "three types of transport once motion has begun: suspension, saltation, and creep. Once small particles are lifted off the ground, eddy currents are able to carry them to considerable heights; in the absence of further turbulent support such particles will soon fall out ... and until they reach the surface, are described as suspended. Particles of intermediate size are lifted by winds to only modest heights, along modified ballistic trajectories, and quickly return to the ground; this motion is called saltation. Finally larger particles may be moved, not by the wind itself, but by momentum exchange with saltating grains; these particles never leave the ground but 'creep' slowly in the direction of the winds." Of these three types of transport, only suspended and saltation particles would be able to abrade the snow and dust. The stratified mixture of snow and dust probably has a relatively low density that range from from less than 0.9 grams per cubic centimeter for water snow and silicate dust to 2 grams per cubic centimeter for ice and siliceous dust (Cutts, 1973b). Further it will be assumed that this "dirty ice" is mechanically weak and can not withstand stresses placed on it due to the extremely low temperatures where snow and/or frost condense out of the atmosphere. Creep as an agent of abrasion is improbable since these large particles would be stopped in the dune field if not at the base of the base of the peripheral ice cap. As cited previously, massive concentric dunes have been found girdling the ice cap. These dunes would therefore consist of saltation particles due to the fact that all terrestrial dunes are made of particles of intermediate size that can not achieve suspension. In addition, Dzurian and Blasius (1975) have observed that the laminated dust and snow layers are remarkably uniform in thickness for large areas. This continuity and uniform thickness strongly favors contemporaneous deposition over a broad area of the polar cap - - hence directly from atmospheric supension of snow, frost, and dust. (Cutts, 1973b). It is unlikely that these laminated layers are composed of saltation particles because dunes are not present. However, terrestrial sandstones are known to have near uniform thicknesses and lateral continuity for hundreds of kilometers. They have been formed by the lateral accretion of dune sand, therefore saltation can not be ruled out entirely. Cutts (1973b) adds that these laminated layers appear to have equal thicknesses. This signifies that deposition was of almost equal volume in either equally spaced intervals or episodic depositional events. Since the depositional events, erosion has cut through these layers to expose this stratification.

Starting particles into motion will require a higher wind velocity for Mars. As mentioned before, the atmospheric density can vary from 0.0155 to 0.02145 kilograms per cubic meter over the polar ice. If these densities are compared to earth's atmospheric density of 1.3045 kilograms per cubic meter, then there will be a need for a higher wind speed to move the same particles. Bagnold (1941) presented an approximate formula for the minium wind drag velocity needed to ? a particular particle. This formula is:

$$V* = A \left(\frac{ogd}{p}\right)^{\frac{1}{2}}$$

He derived this formula through wind tunnel experiments where: V* is that minimum wind drag velocity, A is the parameter that varies with turbulence at the soil surface, g is the gravitational acceleration, d the particle diameter, o the particle density, and p the atmospheric density. Figure 2 will display such a graph of threshold velocity versus particle diameter as calculated by Arvidson (1972).

Another useful formula to compensate for the difference of wind velocity observed above the surface and the wind drag velocity at the surface is:

$$Vz = 5.75\ V*\ \log\frac{Z}{K}$$

Here Vz is the wind velocity at height Z above the surface, V* is the wind drag velocity needed to move a particle, and K is the surface roughness length.

A major problem concerning the origin of the dust and sand in and around the ice cap is the question of where this dust and sand originally came from. Cutts (1973b) suspects that siliceous dust and sand comprise a significant part of the layered deposits. He and McCauley (1973) found evidence of erosional stripping of the Martian surface in the equatorial, middle, and polar latitudes. One such source is the periphery of the great shield volcanoe, Nix Olympica. This feature has a vast circular scarp that indicates scarp recession by numerous landslide tongues. Sharp (1973) also found scarp erosiom in the fretted terrain adjacent to the Tharsis ridge. Elsewhere Sharp points to eolian erosion in troughed terrain and depositional basins. Each of these authors agrees that the removal of this material was accomplished by eolian transport. The quantity of removed dust and sand is estimated by Cutts (1973b) to be 10^7 cubic kilometers. He also estimates that the volume of the layered deposits to be 5×10^6 cubic kilometers. Clearly there is an excess of siliceous debris, the dune fields surrounding the northern polar cap could account for this excess. Reducing the discrepancy further, Sharp (1973b) suggested that the recessional scarp surrounding Nix Olympica may be supplying volatiles to the atmosphere. A Mariner 9 image of Nix Olympica taken during the northern summer, showed clouds concentrated around this peripheral scarp. Though scientists are skeptical of this particular suggestion, there is a consensus that much of this silicate debris originated in the southern hemisphere and was then deposited in the northern hemisphere. This statement and the presence of massive dunes around the ice cap is strongly indicative for high-velocity winds from the south; winds that deposit large saltation particles into dunes with little or no modification by subsequent winds coming off the ice cap.

The most crucial aspects related to the possible eolian origin of the canyons (in the quadrangle N78° to N83° by 330° to 360°) are the seasonal wind directions and the topographic influences on these winds. During the spring and summer, the winds have been observed to spiral clockwise from the North Pole under the Coriolis effect. In the autumn, it is likely that the winds still flow off the ice cap with the same easterly component, following the expected katabatic flow(Cutts, 1973a). Sagan (et al., 1973) has commented that these winds are strong for numerous images show tongues of snow that are 50 kilometers or more in length. In this same direction, several smaller canyons are found on the periphery of the ice cap paralleling these northeasterlies.

The winter climate may be one of vast extremes with the occurrence of several major events. The North Pole will be submerged in darkness for nearly ? 306 days (Cross, 1971), beginning in the latter half of autumn and ending by mid-winter. Mars' axial inclination of 24° will keep these peripheral canyons in darkness for most of this time. The canyon area, like the rest of the polar region, will be extremely cold, and thermal convective turbulence will be suppressed. If the surface winds are low, the fallout rate of suspended dust particles will be accelerated with the precipitation of carbon dioxide and water ices on these particles. Leovy and Mintz (1969) have done a theoretical analysis showing a weak reverse cellular convection. This would slow the rate of precipitation of dust. Near the winter solstice, the planet also reaches perihelion; dust storms will originate around the Noachis and Hellas regions of the southern hemisphere. After initiation of the main phase of the dust storm, dust will gradually spread westward (Leovy et al., 1973). Winds will have a vector component of up to 135 meters per second (Weaver, 1973) going toward the NW or WNW. In less than 14 days, the planet will be shrouded in dust (Gierasch et al., 1972). The dust will lower the albedo for the entire planet absorbing sunlight to power the storm. This type of storm is analogous to a terrestrial hurricane according to Pollack (1975). With the heated air rising, the surrounding cooler air will swiftly move in raising more dust to sustain this storm. Eventually, the temperatures differences planetwide will be greatly diminished as this heated air is circulated. Air temperatures on the surface range from 232° to 262°K (or -41° to -11°C) as measured by Mariner 9 over the South Pole (Gierasch et al.,1972). So the North Pole will probably have similar surface or near-surface temperatures. If these warm southeasterly or east-southeasterly winds are surface or near-surface winds, then they will easily divert the flow of ? the flow of the local winds upon reaching the ice cap. If this wind is a surface wind, then it would lose its energy very rapidly in sublimating and transporting the volatiles and silicate debris the top of the ice cap toward the pole. However, if this wind is a high-altitude wind, then this wind would pass over the peripheral ice cap with no interaction. Instead, a surface wind could be travelling in the opposite direction beneath the southeasterly winds if this storm is analogous to a hurricane. The hurricane idea would have one serious drawback. It would require that winds come from all directions toward the "eye" of the storm and not just from the northwest. And such diverse wind directions would erode the top of the ice cap to a smooth plain as the "eye" of the storm moves westward.

Moving from the speculative winter climate, it is necessary to examine the geomorphic aspects as they might pertain to a cooling southeasterly wind. The proposed southeasterly wind might be self-limiting in the length of the canyons which it could carve. First, the wind will have to ascend over the peripheral edge. In the process, it will expand and lose temperature. The net effect will mean less erosive power exerted on the snow and ice. Second, some of this air mass will travel up the canyons sublimating and transporting the volatiles and silicate debris toward the pole, thus losing more of its energy. After the air mass leaves the canyons near their heads, it will experience a sudden decrease in velocity after leaving the confines of the canyons. The winds will deposit some or most of the eolian particulate matter in the nearby area. As mentioned, the heads of the canyons under study originate at N81.5°. Plate 7 shows the head of such a canyon. There is a possible traverse dune surrounding the canyon rim in much the same manner as a natural levee is found on the floodplain of a river. Behind this "levee" appears to be a traverse dune field extending two to three kilometers beyond the head of the canyon. Yet, one has to be careful in saying that this area could be a dune field because the eastern edge of the field has a scarp of uncertain origin. If the scarp is a flank scarp, then the dune-like features could be a series of tertiary scarps. If it is an eolian scarp similar to the one found at the base of Nix Olympica, then this observation is consistent with the hypothesis of a southeasterly wind. This possible eolian scarp is facing the southwest. Meanning that it could only have been made by a wind acting parallel to the direction of the scarp, and this would role out the possibility of it having been form by a northeasterly wind.

A topographic map also tends to support the idea that the southeasterly wind experiences a rapid loss of kinetic energy. This particular map (see Figure 3) was made by Dzurisin and Blasius (1975). If the topographic contours are close to being correct, then this wind would lose kinetic energy over a short distance and deposit snow and dust just to the north of these canyons near the three and four kilometer contour elevations. This also would be consistent with the southeasterly winds hypothesis in explaining the relatively short lengths of these canyons. On either end of this possible four-kilometer-high ridge are the longer canyons extending further toward the North Pole. However, the U.S. Geological Survey has published its own topographic map, and it indicates a gradual rise from the peripheral ice cap to the smooth field as shown in Figure 4. The Geological Survey's contour information would contradict the hypothesis because this map would leave the relatively short lengths of these canyons unexplained.

Dzurisin and Blasius and the U.S. Geological Survey used four sources of topographic information for their Martian polar maps:(1) S band radio occultation, (2) infrared interferomater spectrometer, (3) ultraviolet spectrometer, and (4) television imaging. The S band radio occultation provided three points for absolute elevation with respect to the radius of the planet. The infrared interferometer spectrometer is best for middle and low latitudes in comparing the emission spectras to a black body emission spectra compensated for albedo and sun angle to arrive at a elevation-to-temperature correlation. The ultraviolet spectrometer made a direct correlation of the carbon dioxide spectrum to atmospheric pressure. Both the infrared interferometer and ultraviolet spectrometers provided indirect atmospheric pressures. Thus both are subjected to atmospheric inhomogenuity. Television imagery by steroscopic examination has given good relative elevations. It is uncertain as to the reliability of this method outside an area without a reference elevation due to the sphericity of the surface. The surprising thing is that both parties used the same sources. However, neither elaborated on their assumptions and/or techniques in deriving two very different topographic maps.

One of the erosional features that the hypothetical wind probably carved were the fluted groves. Plate 8 (an image taken west of the designated region) contains pronounced fluting at the end of the canyon and in the nearby area on the left side of this plate. The groves diverge from the head of the canyon to indicate a high-velocity wind along the length of the canyon. Though this fluting is not decisive evidence of wind direction, it is improbable that the fluting was caused by a wind flowing of the ice cap, concentrating its flow into the head of the canyon and then proceeding to the southeast. First, such a wind should not be able to achieve a sufficient speed to initiate erosion. And second, a wind coming off the ice cap will have an easterly component because of the Coriolis effect. In this case, the image shows no fluting oriented toward the northeast. Plates 3, 4, and 5 will reveal possible fluting on terrace edges and yardangs. The indicated wind direction is along a northwest to southeast axis. It must also be noted that fluting is difficult to determine in the above three plates due to the interferring atmospheric phenomena of "searchlights" and wave clouds.

At this point, the existence and significance of the "searchlight" and wave clouds must be pointed out. The "searchlight" phenomenon is associated with terrace walls and canyon floors. It can be best described as straight diverging bands of contrasting light and darkness that traverse an area regardless of topography below it. (See Plate 6) The phenomenon is typically found over a canyon near the eastern wall with the bands of light extending to the southwest. These observations suggest a meteorological phenomenon related to the changes of pressure for the northeasterly winds. Though this is not an adquate explanation, most authorities agree that it is not a surface feature. Wave clouds are best shown in the lower right corner of Plate 5. Rayner (1978, private communication) explained that these clouds form over high topographical areas such as mountain ranges and high plateaus. Unfortunately, wave clouds are like parting lineation in sandstone in that they indicate fluid-flow direction in one of two opposite directions. In this case, wind direction is probably from the northwest. The reader must remember that this image was not taken during the dust storm of the winter if one was to think this to be southeasterly wind. The reasons that this image could not have been taken during the winter dust storm were (1) the clarity of the atmosphere through the easy identification of topographic features, and (2) that the north polar cap would be submerged in darkness during the time of the storm.

The best explanation for this paradox of wind direction for Plate 5 would be to compare this wind to the Minstral of the Rhone Valley in France. The cold heavy air will rush down into the topographic low area of the Rhone Valley and flow to the low pressure area south of the Rhone River reaching speeds of 80 miles per hour. Admittedly, this type of wind may aid in the erosion of these canyons on Mars, but it is not responsible for the origin of the counterclockwise spiral pattern from the North Pole. Otherwise, these canyons would have a clockwise spiral pattern.

SUMMARY AND CONCLUSIONS

The surface winds near the peripheral edge of the northern ice cap are believed to have contributed to the eolian erosion of the canyons in the southern-most sector of the Martian ice cap. Imagery of the polar region during the spring and summer indicates prevailing northeasterly winds, but moderate to strong northwesterlies should be common only inside the canyons. This wind pattern will persist for most of the Martian year until the global dust storms reach the northern ice cap a few weeks after the winter solstice. The dust storm originates in the Southern Hemisphere and transports dust and heated air, averaging 240°K (Gierasch et al., 1972), into the Northern Hemisphere at velocities reaching 135 meters per second in either a northwest or west-northwest directions. In the southern sector,(N78°to N83° by 330° to 360°), the hypothetical wind might sublimate the volatiles off the top of the ice cap in areas of weaknesses such as crevasses or gaps in traverse snow dunes. These warm, high-velocity winds will continue to excavate the volatiles and siliceous dust at the lower elevations, leaving broad resistant terraces and spiraling canyons. The direct evidence for this southeasterly or east-southeasterly wind is lacking except for the telescopic observations and Mariner 9's temperature readings taken during the 1971 dust storm.

The northern ice cap will have completed over one-half of the 306 days of darkness (Cross, 1971) when the dust storm arrives. The heated air could cut along the top of the peripheral ice cap with the canyons growing in depth and length with each succeeding storm. The relatively short lengths of these canyons, and their heads located at the N81.5° latitude could be attributed to a four-kilometer-high ridge north of the peripheral canyons, provided that Dzurisin's and Blasius's map is correct. This ridge could force the hypothetical southeasterly to precipitate its newly acquired volatiles just north of the canyon heads as the cooling air undergoes an adiabatic expansion. The possible dune field found in Plate 7 and the massive dune fields at the base of the ice cap could be evidence for that southeasterly.

The intracanyon features are even less reliable evidence for a southeasterly wind. It is impossible to determine whether the southeasterly or the northwesterly winds were responsible for the topographic features inside the canyons. The winds for most of the year will be the cold, moderate to strong winds that flow down the canyons onto the surrounding plains. The northeasterly wind will flow over the ice cap and above the canyons, possibly being responsible for the "searchlight" phenomenon. The snow and dust have been assumed to be relatively nonresistant to the action of the southeasterly wind. Yet, the layers are consolidated enough to prevent little eolian erosion by the other winds.

This paper has revealed the uncertainty in studying this region, but much research will have to be made on these peripheral canyons and their associated meteorology. Only then can the existence of this warm southeasterly wind be determined. Unfortunately, this hypothetical southeasterly wind may hide most traces of itself. Excavated snow and dust could be deposited on the four-kilometer-high ridge, and the fluting of most canyons could be blanketed by water snow or frost from the mid-winter storm.

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